Sea Level Rise and Inundation Scenarios for National Parks in South Florida

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Introduction

The National Park Service is tasked with the unimpaired preservation of the natural and cultural resources of the National Park System for the enjoyment, education, and inspiration of current and future generations. This unique mission and perspective positions the National Park Service as a leader in the recognition of, and adaptation to changes in the Earth's climate. It is now unequivocal that climate is warming, and since the 1950s many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, snow and ice have diminished, sea level has risen, and concentrations of greenhouse gases have increased (Steffan et al. 2015, IPCC 2013).

One of the most robust indicators of climate change is rising sea level driven by thermal expansion of warming ocean water and addition of land-based ice-melt to the ocean. Sea level rise is not evenly distributed around the globe, and the response of a regional coastline is highly dependent on local natural and human settings (Cazenave and Le Cozannet 2013). Nowhere is this more evident than in the national parks and preserve located at the southern end of the Florida peninsula, Dry Tortugas National Park, Biscayne National Park, Everglades National Park and Big Cypress National Preserve, where low elevations and exceedingly flat topography provide an ideal setting for encroachment of the sea.

The physical and ecological impacts of sea level rise on these parks will be pronounced and, in some cases, such as in the distribution of mangrove forests, change has already been observed (Krauss et al. 2011). The natural ecological capacity for adaptation and resilience to these changes will be positively impacted through the timely implementation of the Comprehensive Everglades Restoration Plan (CERP), simultaneously protecting the regional water supply for both natural and urban needs (NRC 2014).

Given these current and anticipated changes, it is prudent to define expectations for sea level rise and the associated physical responses over the coming decades. This document is intended to inform the current state of science regarding these expectations.

Sea Level Rise

The Intergovernmental Panel on Climate Change (IPCC) is composed of leading scientists from around the globe whose mission is to review and assess the most recent scientific, technical and socio-economic information relevant to the understanding of climate change. Its most recent assessment, published in 2014, is the Fifth Assessment Report (AR5) which includes projections of global sea level rise based on different Representation Concentration Pathway (RCP) scenarios reflecting possible scenarios for future concentrations of greenhouse gases. RCP8.5 is the highest emission and warming scenario under which greenhouse gas concentrations continue to rise throughout the 21st Century, while RCP6 and RCP4.5 expect substantial emission declines to begin near 2080 and 2040 respectively.

The IPCC sea level rise scenarios are comprehensive, but do not include contributions from a potential collapse of Antarctic ice sheets. However, recent evidence suggests that such a collapse may be underway (Holland et al., 2015; Wouters et al 2015). In addition, the IPCC projections do not account for local processes such as land uplift/subsidence and ocean currents, and do not provide precise estimates of the probabilities associated with specific sea level rise scenarios, which are a crucial decision support metric in the development and assessment of risk. A contemporary study that does estimate local effects and comprehensive probabilities for the RCP scenarios is provided by Kopp et al. (2014). This work is based on a synthesis of tide gauge data, global climate models, and expert elicitation, and includes consideration of the Greenland ice sheet, West Antarctic ice sheet, East Antarctic ice sheet, glaciers, thermal expansion, regional ocean dynamic effects, land water storage, and long-term, local, non-climatic factors such as glacial isostatic adjustment, sediment compaction, and tectonics. Following a review of scientific literature, we have adopted the work of Kopp et al. (2014) as the basis for sea level rise scenarios at the four South Florida national parks.

Datums

A tidal datum provides a geodetic link between ocean water level and a land-based elevation reference such as the North American Vertical Datum of 1988 (NAVD88). The National Tidal Datum Epoch (NTDE) in the United States is a 19-year period over which tidal datums specific to each tide gauge are determined. The current NTDE for the United States is 1983–2001 and sea level rise projections are referenced to the midpoint of this period (1992) consistent with procedures for sea level rise design determined by the U.S. Army Corps of Engineers and NOAA's National Climate Assessment (USACE, 2014). Common tidal datums include mean sea level (MSL), mean high-higher water (MHHW) and mean low-lower water (MLLW) as defined by the National Oceanic and Atmospheric Administration (NOAA 2015). As sea level rises, tidal datum elevations also rise and a new tidal datum is established every 20 to 25 years to account for sea level change and vertical adjustment of the local landmass (NOAA, 2001).

Kopp et al. (2014) use a local mean sea level reference starting in the year 2000 instead of the NTDE MSL datum centered on 1992. To convert these projections to NTDE we estimate mean sea level rise over the 1992 to 2000 period at Vaca Key with an empirical mode decomposition and add the resulting value of 1.4 cm to their projections. All projected water levels are then converted to NAVD88 by subtraction of the 25.3 cm NAVD88 to NTDE MSL offset at the Vaca Key tide station.

Projection

Examination of local sea level rise projections around south Florida finds small differences between Naples, Virginia Key, Vaca Key, and Key West, which are geographically closest to Big Cypress National Preserve, Biscayne National Park, Everglades National Park and Dry Tortugas National Park respectively. We chose the Vaca Key station sea level data as representative of all four natural areas since it reflects local oceanographic processes that influence coastal sea levels around south Florida better than the other three stations.

Regarding selection of greenhouse gas emission scenarios, we employ RCP8.5. Although significant rhetoric is aimed at global emission reduction, emissions continue to escalate and there is presently no clear socio-economic driver to depart from a carbon-based energy infrastructure, and recent assessments of global energy production and population conclude that the RCP4.5 emission scenario is unobtainable, and there is significant uncertainty as to whether the RCP6.0 scenario can be realized (Jones and Warner, 2016).

Each emission scenario and geographic location will have a spectrum of projections that span the possible ranges of sea level rise, and this range is expressed as a probability of occurrence. A probability is commonly understood as the chance or likelihood of an event happening out of a large pool of possible events, and in this case the probability refers to occurrence of a specific sea level rise curve out of the many possible sea level rise curves under a given climate scenario such as RCP8.5. Many different curves are possible for each scenario since there are uncertainties in the observable data (ice sheets, thermal expansion etc.) as well as limitations in the models from which the projections are derived. The median projection (50^{th} percentile) is in the middle of the projections (one-half of the projections are lower, one-half are higher) and can be considered a likely scenario given the current state-of-knowledge. A high percentile projection such as the 99^{th} percentile is one for which it is expected that there is only a 1% chance that sea levels would exceed it, and is considered a worst-case scenario.

Since this projection is intended to inform authorities of anticipated sea level rise for adaptation and planning purposes, and in light of the significant uncertainties inherent in generation of the projections and future dynamics of the climate, it is prudent to consider the upper percentile range of projections. In consideration of these factors we select the RCP8.5 median (50^{th} percentile) as the lower boundary of the projection, and the 99^{th} percentile as the upper boundary. We are therefore conservatively biasing the projections to lie between a lower bound of likely sea level rise and a high projection representing an upper limit to be considered in risk assessments for highly vulnerable, costly, or risk-averse applications. It is emphasized that the high projection is deemed to have only a 1% chance of occurrence under current climate conditions, but in the event of Antarctic ice sheet collapse, its' projected sea level rise is consistent with estimates that include Antarctic ice melt contribution (DeConto and Pollard, 2016).

The sea level rise projection for south Florida referenced to the NAVD88 datum for the RCP8.5 emission scenario and occurrence probabilities of 50% and 99% is shown in figure 1, and is tabulated in Appendix 1. These projections have been offset to match currently observed mean sea level in Florida Bay over the period 2008 to 2015 (Appendix 2), and do not include tides or storm surges. Water levels will be both higher and lower than mean sea level depending on the tidal, weather, and storm conditions.

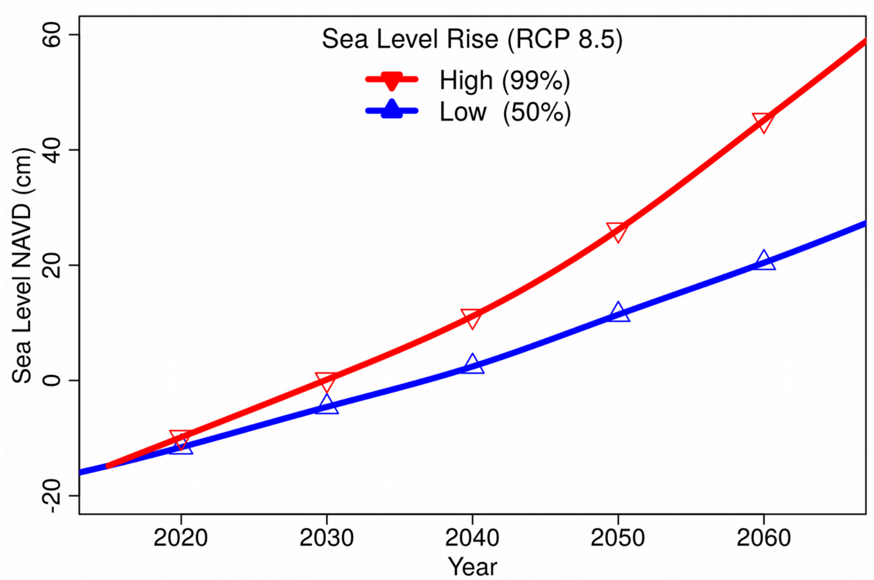

Figure 1. South Florida sea level rise projection in cm NAVD for the RCP8.5 greenhouse gas emission scenario. Low projection in blue is the median (50th percentile), high projection in red (99th percentile). Tides and storm surges are not included in this projection. Values are tabulated in Appendix 1.

Hypsographic Maps

The impact of sea level rise on a landscape is largely controlled by topography. In southwestern Florida, Everglades National Park contains a broad, flat, freshwater slough (Shark River Slough) that connects to the coastal ocean by rivers along the west coast, and by small passes through a slightly elevated marl ridge on the southern coast. Directly south of this coastal ridge is Florida Bay, a basin formed approximately 4,000 years ago as rising sea level flooded the region. In southeastern Florida, Biscayne National Park contains a mangrove fringe bordered by canals and developed properties, and islands within the park are typically less than 2 m above sea level. Not far away are the low-lying islands of Dry Tortugas National Park located about 70 miles west of Key West. Each of these areas will be affected by sea level rise in different ways as shown in figures 2 and 3 which are water level elevation maps based on the sea level rise projections through 2100. These projections do not include tides or storm surge.

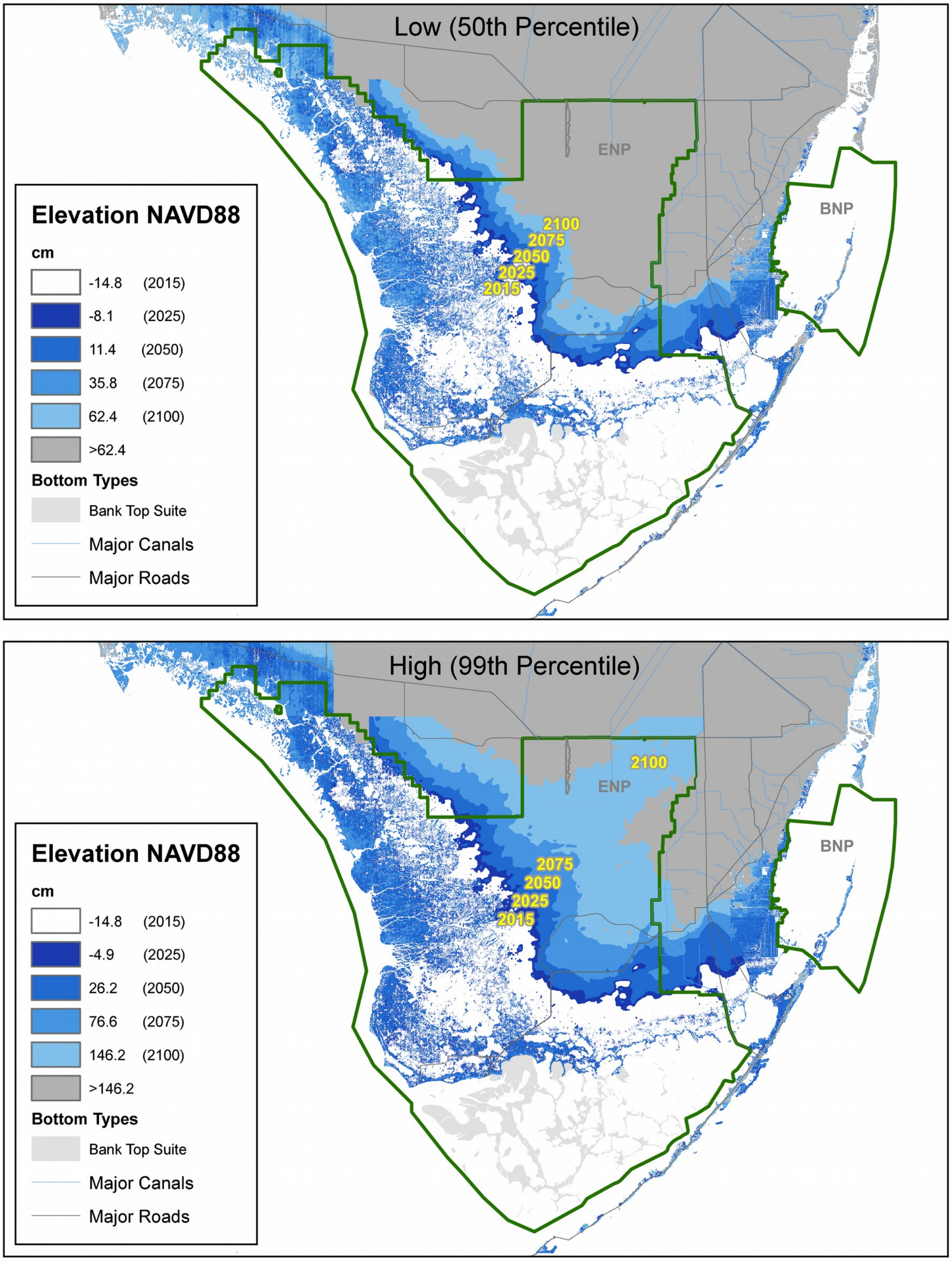

Figure 2. Mean sea level elevation maps for south Florida including Everglades and Biscayne National parks for the median (50th) and high (99th percentile) RCP8.5 projections using current topography and NAVD. Tides and storm surges are not included in this projection.

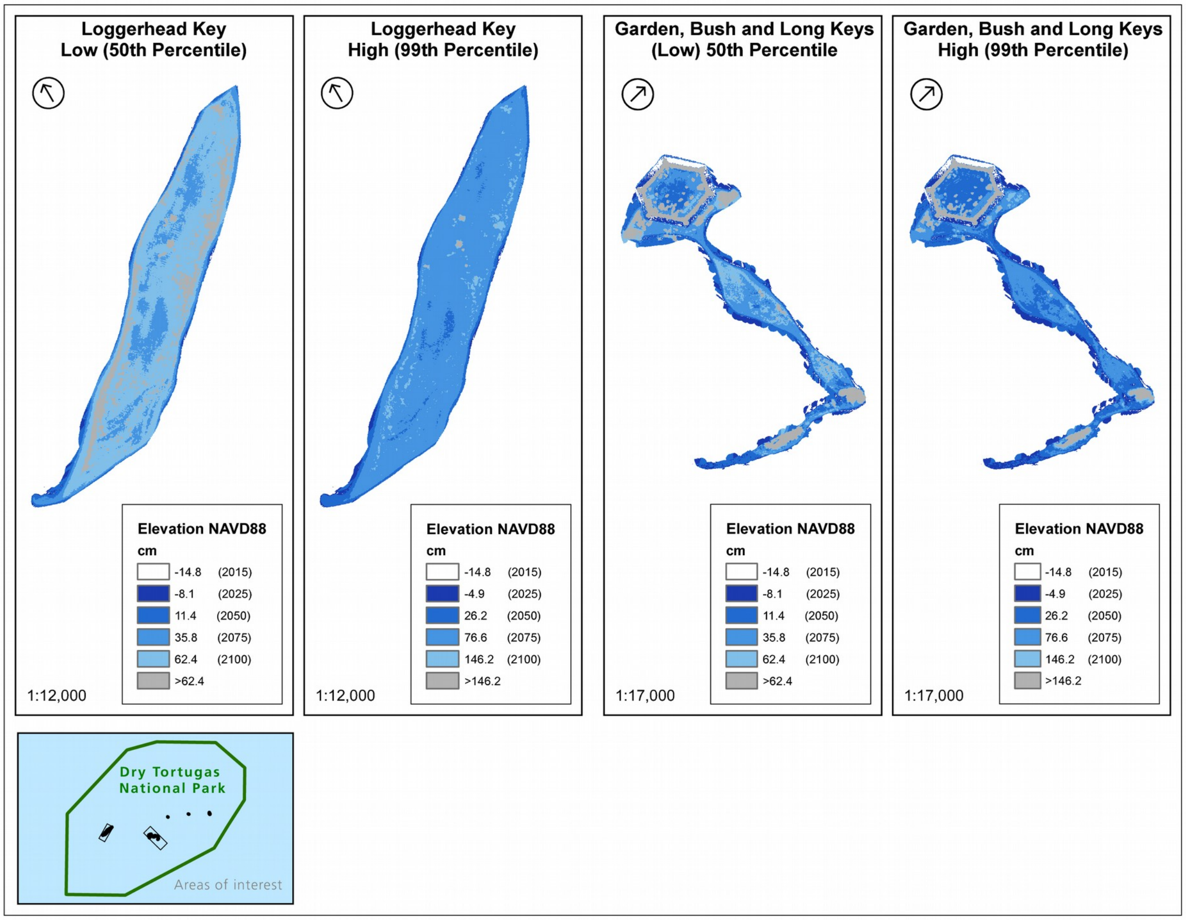

Figure 3. Mean sea level elevation maps for Dry Tortugas National Park showing conditions at Loggerhead, Garden, Bush, and Long Keys for the median (50^{th}) and high (99^{th} percentile) RCP8.5 projections using current topography and NAVD. Tides and storm surges are not included in this projection.

As previously noted, the projections are adjusted to match mean sea level in Florida Bay over the period 2008 – 2015 (-14.8 cm NAVD88) which is represented in the maps with a white color level. This could be somewhat misleading as it suggests that southern Everglades National Park is currently below mean sea level and therefore inundated. However, it is important to understand that this hypsographic analysis is a static representation of a dynamic system and is referenced to land elevations that do not include ecological and biological influences. It simply compares sea level elevation against the height of the land surface and represents where the sea would intrude if the sea level was constant in space and time and there was no water flowing off the marsh or ecological influences. In reality, fresh water flowing off the marsh acts to conteract the influx potential of the sea, and flora such as mangroves create elevated banks which impede inundation such that mean sea level elevations on the maps may not correspond to open water and a marine environment.

For example, figure 4. shows a comparison between the current and projected sea level elevations at the 50th percentile with an aerial photograph of the region near the Ingraham Highway in Everglades National Park. Altough the current mean sea level elevation dominates the lower portion of the region, this is not a marine environment but a transition zone between mangroves and freshwater marsh.

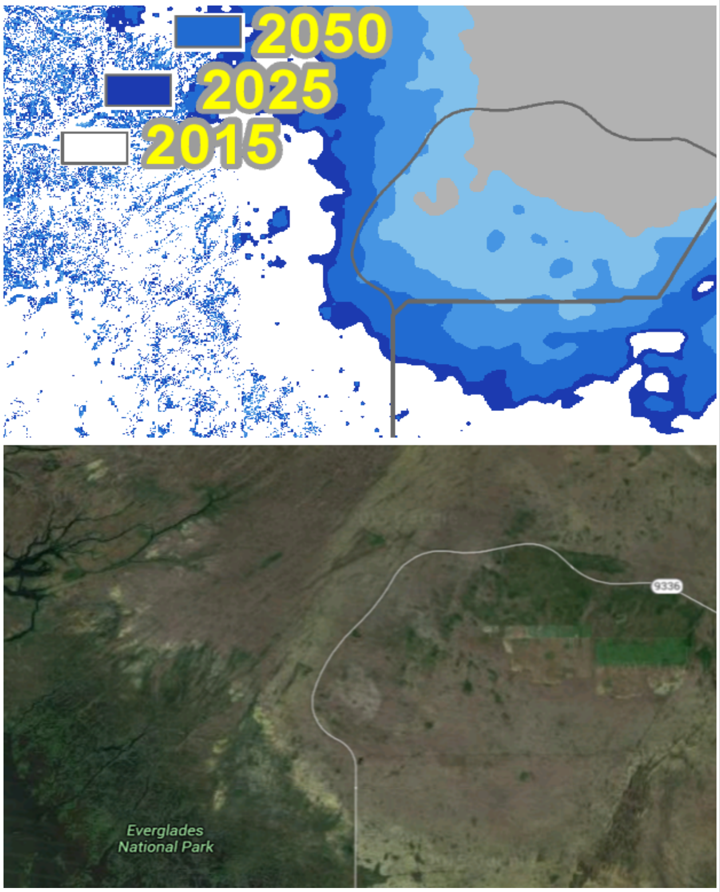

Figure 4. Comparison of sea level elevations (top) with an aerial photograph of a mangrove and marsh transition zone.

Influences of Sea Level Rise

Over the next ten years, represented by the 2025 estimates, dramatic changes in sea level using either the low or high estimates are not anticipated. The expected rise in sea level for the median scenario is 6.7 cm and the high estimate is 9.9 cm. The 3.2 cm difference between the two estimates is not enough to make much of a difference on the topography of Shark Slough or the coastal fringe of Florida Bay. There is likely to be increased inundation of the mangrove islands along the Shark River Estuary and the potential for landward encrouchment of mangrove forest is likely. However, the buttonwood ridge located along the north shore of Florida Bay coastal ridge remains above sea level as does the majority of the freshwater slough.

The modest increase expected by 2025 is not likey to impact the terrestrial portions of Dry

Tortugas or Biscayne National Park. At Biscayne NP, the trend toward marine conditions can be expected to continue and increased sea level will likely reduce freshwater flow from the Biscayne Bay Coastal Wetlands and from the canal system. At DRTO, only a fringe around the coastline is expected to be exceeded by the sea level.

By 2050 sea level is expected to increase between 26 and 41 cm. The effect on Shark Slough is similar for each estimate of rise; a fairly uniform magnitude of landward encroachment can be expected. Taylor Slough also becomes significantly impacted by the encroaching sea in both scenarios with the influence of the sea making its way up the slough perhaps as far as the Old Ingraham Highway. However, the eastern panhandle of the Park is much more heavily impacted by the high estimate of sea level rise than the median estimate. This is simply because the high estimate of 41 cm exceeds the land surface threshold in this area and begins to over top the buttonwood ridge.

In 2075, the impacts represented by the median estimate is similar to those of the high estimate of 25 years earlier. Sea level is likely to exceed that of the buttonwood ridge with sea water influence approaching the main park road (Ingraham Highway).

By 2100 the median estimate suggests that sea level will exceed the land surface elevation throughout Taylor Slough and also dominate the region near the Ingraham Highway. In the high estimate, virtually all of Shark Slough is likely to also be influenced by the sea. In the case of the low-lying islands of Biscayne and Dry Tortugas national parks, many of these features can be expected to become submerged.

One important caveat is that these inundation projections do not account for land elevation changes, either positive or negative, as may be observed as water level and salinity change over time. It is well understood that increased freshwater flow, as expected with Everglades restoration efforts, will help to protect against freshwater peat collapse by maintaining soil elevation and reduce the extent of saltwater intrusion.

Florida Current

These mean sea level estimates represent the contemporary state-of-the-art in local sea level rise projection. However, knowledge of all processes and feedbacks driving sea levels is limited, and the models on which these projections are based are necessarily incomplete. The models do not have the spatial resolution required to resolve fine-scale oceanographic processes such as variability in the Florida Current. The Florida Current is one of the strongest and most climatically important ocean currents and forms the headwater of the Gulfstream (Gyory et al., 1992). As the Florida Current fluctuates in intensity, sea levels along the Atlantic coast of Florida respond to a geostrophic balance by falling when the current increases, and rising when current decreases (Montgomery, 1938).

The Gulfstream and Florida Current are components of the Atlantic meridional overturning circulation (AMOC), a component of the global ocean conveyor belt. Climate models agree that as the ocean warms and fresh meltwater is added there will be a decline in the strength of the AMOC (Rahmstorf et al. 2015). If the Florida Current decreases in strength then sea levels will rise along the Florida east coast and in Florida Bay which is the southern-most extent of Everglades National Park. The extent of this change is difficult to forecast, but recent evidence suggests that a 10% decline in transport has contributed 60% of the roughly 7 cm increase in sea level at Vaca Key over the last decade (Park and Sweet 2015). It is therefore plausible that a drastic slowdown of the AMOC and Florida Current could contribute an additional 10 to 15 cm of sea level rise to south Florida over this century. This potential is not reflected in the sea level rise projections, but should be acknowledged by authorities and planners that use them.

Inundation and Nuisance (Recurrent) Flooding

Sea level rise is slow and difficult to discern when compared to the dynamic impacts of changing seasons and storms. A drastic change in sea level requires centuries or millennia, however, pronounced changes in the frequency and heights of coastal inundation along low-lying coastlines can occur in decades, and such changes are now evident around the United States over the last few decades as sea levels rise (Sweet and Park, 2014). For example, the number of daily water level exceedences per year above the 1993 – 2011 mean water level in Long Sound of Florida Bay within Everglades National Park is shown in figure 5. The curves show best-fit models based on general linear and geometric growth, suggesting that in the last decade the frequency of low-level inundations has transitioned from a slow, steady increase to one of escalating occurrences.

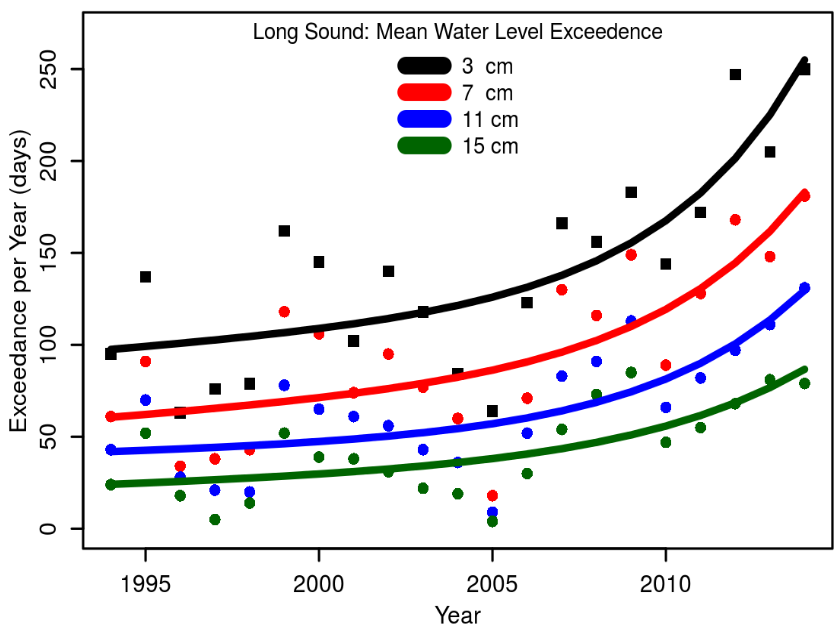

Figure 5. Daily water level exceedances above the 1993 – 2011 mean water level in Long Sound of Florida Bay, Everglades National Park.

These changes are a consequence of sea level rise transitioning high water level exceedences from low-chance events to common events, and this change is accelerating.

Infrequent-High Impact Flooding (Storm Surge)

Although sea level rise and the associated increases in recurrent flooding are important physical stresses on south Florida natural areas, it is the infrequent, but high-impact storm surge events that drastically change the landscape over the course of a few hours. For example, Hurricane Wilma in 2005 had a profound impact on the ecology of the Cape Sable region of Everglades National Park (Smith et al. 2009, Whelan et al. 2009) producing extensive damage at the Flamingo Visitor Center of Everglades National Park permanently closing a hotel and restaurant.

Storm surge is highly dependent on the severity and path of the storm, as well as the local bathymetric and topographic features of the coast, and since they occur infrequently it is difficult to develop robust predictions of these rare events. A popular approach is to fit an extreme-value probability distribution to the highest water levels observed at a water level monitoring gauge. However, gauges have short periods of record, typically a few decades at most, and they fail or are destroyed during extreme storms such that peak water levels are not recorded. A predictive storm surge database, SurgeDat was developed in part to address this shortcoming by providing a statistical combination of data from multiple events within an area of interest (Needham et al., 2013). SurgeDat records storm surge water levels from all available sources, often from post-event high-water marks where gauge data are not available. SurgeDat then applies a statistical regression to estimate storm surge recurrence intervals. A recurrence interval is the length of time over which one can expect a storm surge to meet or exceed a specific inundation level. A familiar example is the 100-year flood level, which is really a 100-year recurrence interval at the specified flood level. In other words, in any one year there is a 1/100, or 1% chance that the flood level will be matched or exceeded. An excellent discussion of this can be found at the United States Geological Survey webpage water.usgs.gov/edu/100yearflood.html.

Relevant to south Florida, a subset of SurgeDat was selected within a 25 mile radius of 25.2° N, 80.7° W and is tabulated in Appendix 3. Based on these events, the SurgeDat projection for storm surge recurrence intervals (figure 6) suggest that a 180 cm (6 ft) surge event can be expected every 20 years. This same level of sea level rise is not anticipated to occur until at least 2100.

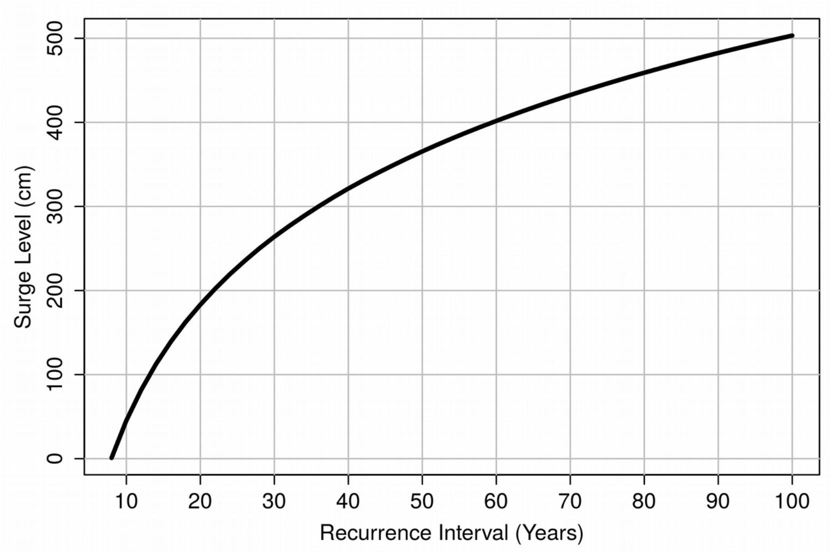

Figure 6. Storm surge recurrence intervals from the SurgeDat database and Return Periods Predictor for a 25 mile radius centered on 25.2° N, 80.7° W.

The recurrence interval projection is by necessity based on a sparse data set, and caution should be used in its interpretation. As projection intervals become longer, it is more likely that the observed data are inadequate to robustly represent all possibilities. Also, these projections do not incorporate changes from sea level rise, or from a changing climate which can alter the strength and frequency of storms. An important aspect of sea level rise is that it significantly shortens the expected recurrence intervals of storm surge. For example, under a median sea level rise projection at Key West, Park et al. (2011) find that a 1-in-50 year storm surge based on historic data in 2010 can be expected to occur once every 5 years by 2060.

Conclusion

Sea level rise is one of the most robust indicators of climate change and a warming planet. The national parks of south Florida are intimately tied to the ocean, and are already experiencing physical and ecological changes in response to sea level rise. Based on a review of the available science, we have developed a projection to inform park interests on anticipated sea level rise and inundation, trends in the frequency of nuisance flooding, and recurrence intervals of storm surge. The sea level rise projections are based on the RCP8.5 emissions scenario published by the ICPP AR5, as this scenario is deemed the most likely given the current inability of the global industrial complex to realistically pursue emission reductions. Two estimates are provided which bracket the anticipated range of sea level rise. The low projection is the 50th percentile (median) forecast, while the high projection is intended for worst-case planning and corresponds to the 99th percentile, there is only a 1% chance that mean sea level will reach or exceed this level. However, these projections do not incorporate contributions from a collapse of Antarctic ice-sheets, changes in the Florida Current, or inundation due to tides or storms. Although the high projection is deemed to have only a 1% chance of occurrence under current conditions, a collapse of the Antarctic ice-sheets could render it more plausible.

Management actions in natural coastal systems will necessarily be location and project specific. An appropriate planning horizon is a crucial component of managerial design since benefits observed today may be offset by changing conditions within the planned lifespan of the project. There will most certainly be updates to the climate projections presented here and adaptive management practices should be incorporated when considering project alternatives, and, when appropriate, preference given to solutions that are flexible and can be adjusted as our understanding of current and anticipated impacts changes. These practices should be institutionalized as part of the ongoing monitoring and assessment process, incorporated into our education and outreach efforts, and used to best manage the influence of climate change on park resources.

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Appendix 1A Sea Level Rise Projection : NAVD88 (cm)

Sea Level Rise in cm NAVD88 from Kopp et al. (2014) at Vaca Key. Values between decades (2010, 2020, etc.) have been interpolated with a cubic spline. Low is the 50th percentile of the RCP8.5 projection, High the 99th percentile. An offset of 1.4 cm has been added to convert to the NTDE MSL datum by accounting for sea level rise from 1992 to 2000. Elevations are converted to NAVD88 datum by subtraction of 25.3 cm from the NTDE MSL values. The projections have been offset to match observed mean sea level over the period 2008 – 2015 in Florida Bay (Appendix 2).

Year	Low	High	Year	Low	High	Year	Low	High	Year	Low	High
2015	-14.8	-14.8	2045	6.8	18	2075	35.8	76.6	2105	68.3	159.9
2016	-14.2	-13.8	2046	7.7	19.6	2076	36.9	79	2106	69.5	162.7
2017	-13.6	-12.8	2047	8.6	21.1	2077	38	81.5	2107	70.8	165.4
2018	-12.9	-11.8	2048	9.6	22.8	2078	39.2	84	2108	72	168.3
2019	-12.3	-10.8	2049	10.5	24.4	2079	40.3	86.5	2109	73.2	171.2
2020	-11.6	-9.8	2050	11.4	26.2	2080	41.4	89.2	2110	74.4	174.2
2021	-10.9	-8.9	2051	12.3	27.9	2081	42.6	91.8	2111	75.6	177.2
2022	-10.2	-7.9	2052	13.2	29.7	2082	43.7	94.5	2112	76.7	180.3
2023	-9.5	-6.9	2053	14.1	31.6	2083	44.8	97.2	2113	77.9	183.5
2024	-8.8	-5.9	2054	15	33.5	2084	45.9	100	2114	79	186.8
2025	-8.1	-4.9	2055	15.9	35.4	2085	47.1	102.8	2115	80.1	190.1
2026	-7.4	-3.9	2056	16.8	37.3	2086	48.2	105.6	2116	81.2	193.4
2027	-6.7	-2.9	2057	17.7	39.3	2087	49.3	108.5	2117	82.2	196.8
2028	-6	-1.9	2058	18.6	41.2	2088	50.3	111.3	2118	83.3	200.2
2029	-5.3	-0.9	2059	19.5	43.2	2089	51.4	114.2	2119	84.4	203.7
2030	-4.6	0.2	2060	20.4	45.2	2090	52.4	117.2	2120	85.4	207.2
2031	-3.9	1.2	2061	21.4	47.1	2091	53.4	120.1			
2032	-3.2	2.2	2062	22.3	49	2092	54.4	123			
2033	-2.6	3.2	2063	23.3	51	2093	55.4	125.9			
2034	-1.9	4.3	2064	24.3	52.9	2094	56.3	128.9			
2035	-1.2	5.3	2065	25.3	54.9	2095	57.3	131.8			
2036	-0.5	6.4	2066	26.3	56.9	2096	58.3	134.7			
2037	0.2	7.6	2067	27.3	58.9	2097	59.3	137.6			
2038	0.9	8.7	2068	28.3	60.9	2098	60.3	140.5			
2039	1.6	9.9	2069	29.4	63	2099	61.3	143.3			
2040	2.4	11.2	2070	30.4	65.2	2100	62.4	146.2			
2041	3.2	12.4	2071	31.5	67.3	2101	63.5	148.9			
2042	4.1	13.8	2072	32.6	69.6	2102	64.7	151.7			
2043	5	15.1	2073	33.6	71.8	2103	65.9	154.4			
2044	5.9	16.6	2074	34.7	74.2	2104	67.1	157.1			

Appendix 1B Sea Level Rise Projection : NAVD88 (ft)

Sea Level Rise in feet NAVD88 from Kopp et al. (2014) at Vaca Key. Values between decades (2010, 2020, etc.) have been interpolated with a cubic spline. Low is the 50th percentile of the RCP8.5 projection, High the 99th percentile. An offset of 0.55 inches has been added to convert to the NTDE MSL datum by accounting for sea level rise from 1992 to 2000. Elevations are converted to NAVD88 datum by subtraction of 0.83 feet from the NTDE MSL values. The projections have been offset to match observed mean sea level over the period 2008 – 2015 in Florida Bay (Appendix 2).

Year	Low	High	Year	Low	High	Year	Low	High	Year	Low	High
2015	-0.49	-0.49	2045	0.22	0.59	2075	1.17	2.51	2105	2.24	5.25
2016	-0.47	-0.45	2046	0.25	0.64	2076	1.21	2.59	2106	2.28	5.34
2017	-0.45	-0.42	2047	0.28	0.69	2077	1.25	2.67	2107	2.32	5.43
2018	-0.42	-0.39	2048	0.31	0.75	2078	1.29	2.76	2108	2.36	5.52
2019	-0.40	-0.35	2049	0.34	0.80	2079	1.32	2.84	2109	2.40	5.62
2020	-0.38	-0.32	2050	0.37	0.86	2080	1.36	2.93	2110	2.44	5.72
2021	-0.36	-0.29	2051	0.40	0.92	2081	1.40	3.01	2111	2.48	5.81
2022	-0.33	-0.26	2052	0.43	0.97	2082	1.43	3.10	2112	2.52	5.92
2023	-0.31	-0.23	2053	0.46	1.04	2083	1.47	3.19	2113	2.56	6.02
2024	-0.29	-0.19	2054	0.49	1.10	2084	1.51	3.28	2114	2.59	6.13
2025	-0.27	-0.16	2055	0.52	1.16	2085	1.55	3.37	2115	2.63	6.24
2026	-0.24	-0.13	2056	0.55	1.22	2086	1.58	3.46	2116	2.66	6.35
2027	-0.22	-0.10	2057	0.58	1.29	2087	1.62	3.56	2117	2.70	6.46
2028	-0.20	-0.06	2058	0.61	1.35	2088	1.65	3.65	2118	2.73	6.57
2029	-0.17	-0.03	2059	0.64	1.42	2089	1.69	3.75	2119	2.77	6.68
2030	-0.15	0.01	2060	0.67	1.48	2090	1.72	3.85	2120	2.80	6.80
2031	-0.13	0.04	2061	0.70	1.55	2091	1.75	3.94			
2032	-0.10	0.07	2062	0.73	1.61	2092	1.78	4.04			
2033	-0.09	0.10	2063	0.76	1.67	2093	1.82	4.13			
2034	-0.06	0.14	2064	0.80	1.74	2094	1.85	4.23			
2035	-0.04	0.17	2065	0.83	1.80	2095	1.88	4.32			
2036	-0.02	0.21	2066	0.86	1.87	2096	1.91	4.42			
2037	0.01	0.25	2067	0.90	1.93	2097	1.95	4.51			
2038	0.03	0.29	2068	0.93	2.00	2098	1.98	4.61			
2039	0.05	0.32	2069	0.96	2.07	2099	2.01	4.70			
2040	0.08	0.37	2070	1.00	2.14	2100	2.05	4.80			
2041	0.10	0.41	2071	1.03	2.21	2101	2.08	4.89			
2042	0.13	0.45	2072	1.07	2.28	2102	2.12	4.98			
2043	0.16	0.50	2073	1.10	2.36	2103	2.16	5.07			
2044	0.19	0.54	2074	1.14	2.43	2104	2.20	5.15			

Appendix 2 Mean Sea Level in Florida Bay

Mean sea level (MSL) was determined by averaging data over the last 7 years at three sea level stations across Florida Bay. Sea levels were first aggregated into daily averages, followed by a 30-day moving average at each station. The MSL estimate consists of an average of these three stations from July 1st 2008 through July 1st 2015 as shown in figure A2, and this MSL value of 0.97 ft NGVD29 or -14.8 cm NAVD88 is used as the starting point of the projections in 2015.

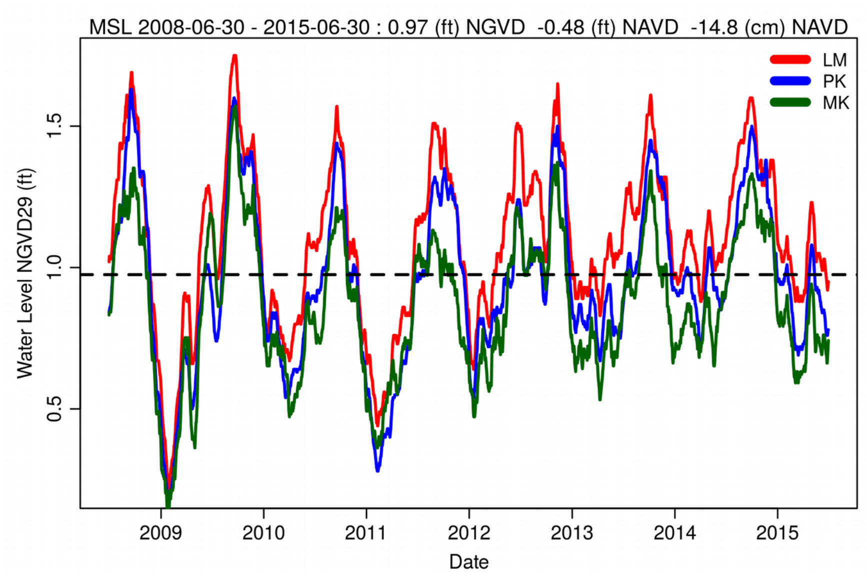

Figure A2. 30 day moving averages of daily mean sea level at Murray Key (MK), Peterson Key (PK) and Little Madiera Bay (LM) in Florida Bay. The dashed line is the mean of all three data sets.

Appendix 3 SurgeDat Database for Florida Bay

Storm Name	Year	Longitude	Latitude	Surge (m)	Datum	Location
Katrina	2005	-81.0369	25.1294	1.22		Extreme SW Florida
Inez	1966	-80.5297	24.9976	1.10	Above Normal	Plantation Key
Alma	1966	-80.5135	25.0110	0.30	Above Normal	Tavernier
Gordon	1994	-80.5139	25.0108	1.22	Above Sea Level	Upper Florida Keys
Betsy	1965	-80.5148	25.0096	2.35	Mean Low Water	Tavernier
Donna	1960	-80.6353	24.9133	4.11		Upper Matecumbe Key
Andrew	1992	-80.9120	25.1431	1.50		Flamingo
Rita	2005	-80.7200	24.8605	1.22	NGVD 29	Middle and Upper Keys
Unnamed	1929	-80.3885	25.1848	2.68	Mean Sea Level	Key Largo
Wilma	2005	-81.0352	25.3523	2.50		Shark River 3
Gladys	1968	-80.5135	25.0110	0.15	Above Normal	Tavernier
David	1979	-80.6263	24.9231	0.61	Above Normal	Islamorada
Labor Day	1935	-80.7375	24.8516	5.49		Lower Matecumbe-Ferry Slip - Camp 3

Recurrence Interval projection in Years from the Florida Bay data. Note that this projection does not take into account future sea level rise.

Interval (Yr)	Surge (cm)	Interval (Yr)	Surge (cm)
10	45	56	388
12	82	58	395
14	112	60	402
16	139	62	408
18	162	64	415
20	183	66	421
22	202	68	427
24	219	70	433
26	235	72	438
28	250	74	444
30	264	76	449
32	277	78	454
34	289	80	459
36	300	82	464
38	311	84	469
40	321	86	473
42	331	88	478
44	340	90	482
46	349	92	487
48	357	94	491
50	365	96	495
52	373	98	499
54	381	100	503